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Characterization of Voltage Sags and its Mitigation Using Custom Power Devices in Emerging Power System

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Abstract

Voltage sags are short duration reductions in RMS voltage caused by short circuits, overloads and starting of large motors. Voltage sag has much a global problem. For proper analysis and mitigation of voltage sag, their characterization is important to be analized. The magnitude and duration are the main characteristics of voltage sag. In this paper voltage sag and their characteristics have been presented in a comprehensive way. This paper analized how voltage sags occur, what their characteristics are and the impact on equipments behavior for different conditions. Through voltage source converter, it is possible to compensate for the drop in system voltage or even to temporarily take over the supply completely. The shunt and series controller are based on power-electronic voltage source converters. For a full compensation both reactive and active power are needed. Not only for deep voltage sags but it is also possible to compensate the drop in voltage magnitude by injecting reactive power only.

Keywords: *Characterization, Monitoring, Phase-angle-jump, point-on-wave, Voltage sag etc*

1. Introduction

Power quality has been the focus of considerable research in recent years. Voltage sags, in particular, can cause expensive downtime. Voltage sags are defined as a short duration reductions in RMS voltage, caused by short circuits, overloads, starting of large motors. The interest of voltage sags is mainly due to the problems which caused on several types of equipment: adjustable-speed drives, process control equipment, and computers are notorious for their sensitivity.

Some equipments trip when the RMS voltage drops below 90% for longer than one or two cycles. It will clear that such an equipment will trip tens of time in a year. If this is the process control equipment of a paper mill, one can imagine that the damage of voltage sags can be so enormous. Voltage sag has much a “global” problem. A Voltage sag due to a short-circuit fault is shown in Figure 1. It can be seen that the voltage amplitude drops to 20% of pre fault voltage for about two cycles. After these two cycles, the voltage comes back to the pre-sag voltage. This magnitude and duration are the main characteristics of voltage sag. During-sag voltage contains a large amount of high frequency components [6, 7]. Figure 1 also shows a small overshoot in voltage immediately after the sag.

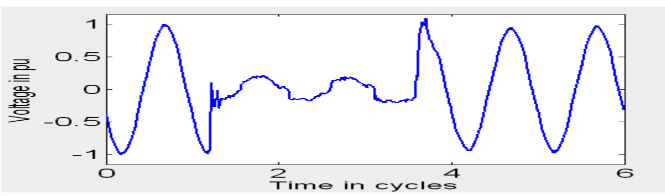

Figure 1. A voltage sag due to a short-circuit fault

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The current interest in voltage sags is to short-circuit faults. These voltage sags are the one which caused the majority of equipment to trip. Starting of induction motors also leads to voltage sags. This paper presents, in a comprehensive way, how voltage sags occur, what their characteristics are and the impact on equipments behavior. All the figures are obtained by using MATLAB simulations. It is obvious that the second infeed significantly reduces the voltage drop. From the critical distance, the exposed length can be calculated. For higher critical, voltage is more sensitive equipment than the exposed length depends on the number of feeders originating from the two busses. The distance between the substations has been increased to assume in km, then all other parameter were kept. The amount of active power taken from the supply is increased and the active power requirement of the controller is reduced. For leading power factor, a negative phase-angle jump increases the active power requirements. For a single-phase controller, the characteristic voltage does not have much practical meanings. For increasing impedance angle, we observed an increase in active power, especially for smaller values of the source impedance. A single-phase controller is the injected power in each of the three-phases.

2. Voltage Sag Magnitude
2.1 Monitoring

The magnitude of voltage sag can be determined in a number of ways. Mostly, existing monitors obtain the sag magnitude from the RMS voltages. There are several alternative ways of quantifying the voltage level. As long as the voltage is sinusoidal, it does not matter whether RMS voltage, fundamental voltage, or peak voltage is used to obtain the sag magnitude. But especially during voltage sag, this is not the often case [1].

2.1.1 RMS Voltage

As voltage sags are initially recorded as sampled points in time, the RMS voltage will have to be calculated from the sampled time-domain voltages. This is done by using the following equations.

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \qquad (1)$$

Where N is the number of sample per cycle and v_i is the sample voltages in time domain. In Figure 2, the RMS voltage has been calculated over a window of one cycle, which has 256 samples.

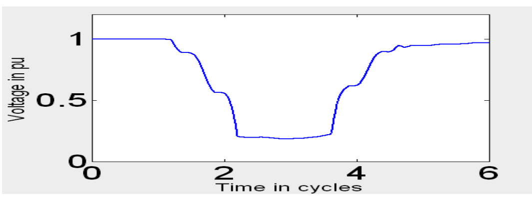

Figure 2. One-cycle RMS voltage for the voltage sag

2.1.2 Fundamental Voltage Component

By using the fundamental component of the voltage, it has the advantage that the phase-angle jump can be also be determined at the same time. The fundamental voltage component as a function of time can be calculated as,

$$V_{fund}(t) = \frac{2}{T}\int_{t-T}^{t} v(\tau)e^{j\omega_0\tau}d\tau \qquad (2)$$

The absolute value of this complex voltage is the voltage magnitude as a function of time, its argument can be used to obtain phase-angle jump. The absolute value of fundamental component is shown in Figure 3. Each point represents the magnitude of complex fundamental component of previous cycle (256 points). Figure 4 shows that transition from pre-fault to during fault is clearly faster. It means the transition time is very less or transition period ends very rapidly.

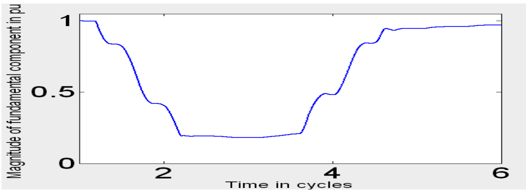

Figure 3. Magnitude of the fundamental component of the voltage sag

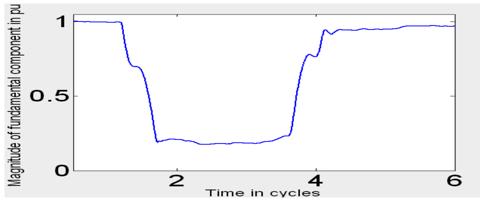

Figure 4. Magnitude of the fundamental component of the voltage sag obtained by using a half-cycle window

2.1.3 Peak Voltage

The peak voltage as a function of time can be obtained by using the following expression: with *v(t)*

$$V_{peak} = \max_{0<\tau<T} |v(t-\tau)| \tag{3}$$

as the sample voltage waveform and T as an integer of the multiple of one half-cycle. In Figure 5, for each sample, the maximum of the absolute value of the voltage over the preceding half-cycle has been calculated.

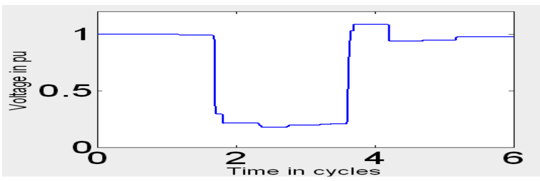

Figure 5. Half-cycle peak voltage for the voltage sag

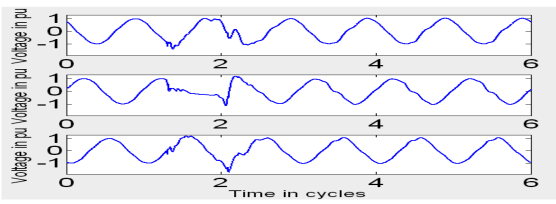

Figure 6. Time-domain plot of a one-cycle sag of three phase voltages

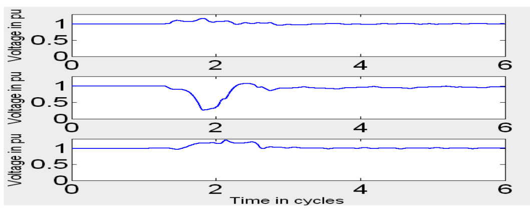

Figure 7. Half-cycle RMS voltages for the voltage sag

2.1.4 A One-Cycle Voltage Sag

Another case of voltage sag is shown in Figure 6. which all three phase voltages are shown. The voltage is low in one phase for about one cycle and recovers rather fast after that.

The other two phases show some transient phenomenon, but no clear sag or swell. Figure 7 gives the half-cycle RMS value for the sag which is shown in Figure 6. It is better and more accurate to analyse the voltage sag by this way.

If the monitor takes one sample every half-cycle the resulting sag magnitude can be anywhere between 26% and 70% depends on the moment at which the sample is taken. The half-cycle peak voltage is shown in Figure 8.

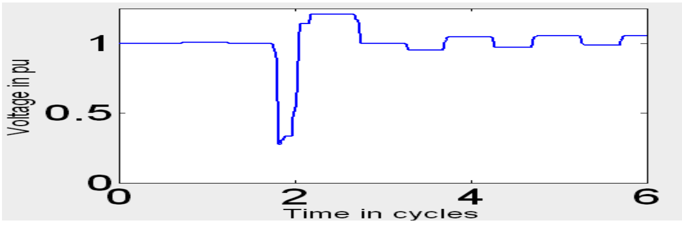

Figure 8. Half-cycle peak voltage for phase b of Figure 6

2.1.5 Obtaining One Sag Magnitude

This characterizing the sag method is recommended in a number of IEEE standards (493-1998, 1159-1995, and 1346-1998). The international Union of Producers and distributors of Electric Energy recommend using the nominal voltage as a reference [2], [3].

2.2 Theoretical Calculations

The sag magnitude as a function of the distance to the fault has been calculated for a typical 11 kV overhead line. For the calculations, a 150 mm^2 overhead line and fault levels of 750 MVA, 200 MVA, and 75 MVA is used. The fault level is used to calculate the source impedance at the pcc and the feeder impedance between the pcc and the fault. The source impedance is purely reactive, thus $Z_s = j0.161\ \Omega$ for the 750 MVA source. The impedance of the line is 0.117+j0.315 Ω per km.

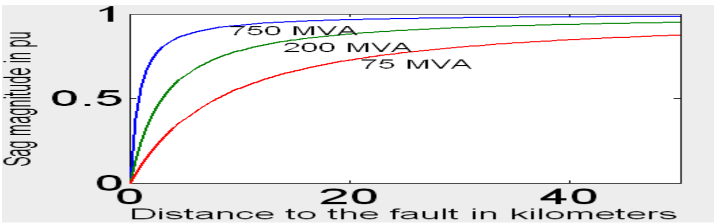

Figure 9. Sag magnitude as a function of distance to the fault, for fault on 11 kV, 150mm^2 overhead lines

The sag magnitude increases (i.e. the sag becomes less severe) distance to the fault and the fault level. The fault at tens of kilometers distance may still cause severe sag.

2.2.1 Influence of Cross Section

Overhead lines of different cross section have different impedance. This is true for cables also. Therefore, it is expected that the cross section of the line or cable influences the sag magnitude. If cross section of overhead lines or cables increases, sag becomes severe. Figure 10 and figure 11 show sag magnitude versus distance plot for overhead lines and cables respectively.

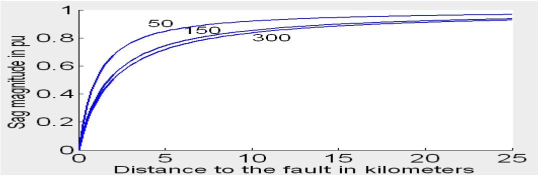

Figure 10. Sag magnitude versus distance, for 11 kV, overhead lines with different cross sections

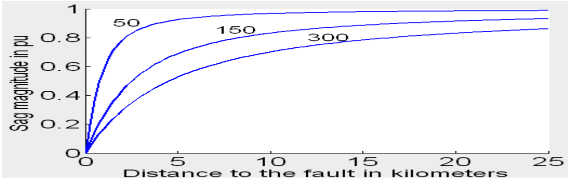

Figure 11. Sag magnitude versus distance, for 11 kV, underground cables with different cross sections

2.2.2 Fault behind Transformers

The impedance between the fault and pcc not only consists of lines or cables but also of power transformers. As transformers have rather large impedance, among others to limit the fault level on the low-voltage side, the presence of a transformer between the fault and pcc will lead to relatively shallow sags.

Figure13 shows sag magnitude versus distance plot for various voltage levels. The horizontal length is determined by the maximum length of feeders at voltage levels. For 400 kV a length of 200 km has been taken. The short length of the 132 kV feeders shows that sags due to faults at 132 kV are always deep.

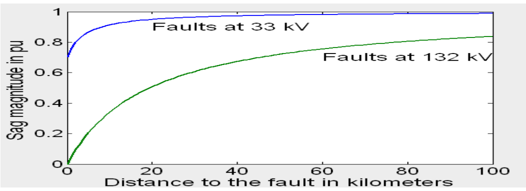

Figure 12. Comparison of Sag magnitude for 132 kV and 33 kV faults

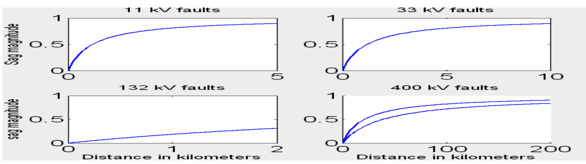

Figure 13. Sag magnitude vs. distance for faults at various voltage levels in supply

2.2.3 Sag Magnitude in Non-Radial Systems

From Figure 14, the bottom curve gives the sag magnitude at the 11 kV bus for fault at a 66 kV feeder when the 11 kV generator is not in operation. In that case, the sag magnitude at 11 kV equals the sag magnitude at 66 kV because all load currents have been neglected. The top curve gives the sag magnitude at 11 kV bus with on-site generator connected. Due to the generator keeping up the voltage at the 11 kV bus, the sag magnitude never drops below 26%.

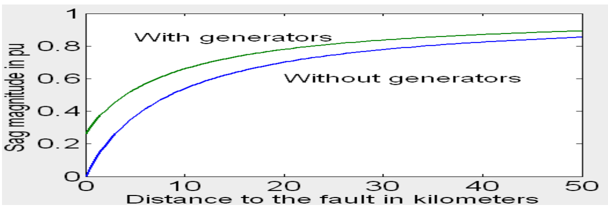

Figure 14. Sag magnitude versus distance, with and without on site generator

3. Voltage Sag Duration

3.1 Fault-Clearing Time

Generally, fault in transmission systems are cleared faster than fault in distribution systems. In transmission systems, the critical fault-clearing time is rather small. Thus, fast protections and fast circuit breakers are essential. Also transmission and sub-transmission systems are normally operated as a grid, requiring distance protection or differential protection, both of them are rather fast. The principal form of protection in distribution systems is over current protection. This often requires some time grading which increases the fault clearing time [4], [5]. An overview of the fault clearing time of various protective devices is given as following:

- current-limiting fuses: less than one cycle
- expulsion fuses: 10-1000 ms
- distance relay with fast breaker: 50-100 ms
- differential relay: 100-300 ms
- overcurrent relay: 200-2000 ms

3.2 The Measurement of Sag Duration

A common used definition of sag duration is the number of cycles during which the RMS voltage is given below a threshold. This threshold will be somewhat different for each monitor but typical values are around 90%. A power quality monitor will typically calculate the RMS value once every cycle.

Measured sag with a long post-fault component is shown in Figure 15 below. The three phase voltages are shown, to better indicate the post-fault voltage sag. The sag is unbalanced during fault, but then balanced after fault is cleared. The RMS voltage versus time for the sag is shown in Figure 16. A large drop in voltage in two phases and a small one in third phase is observed.

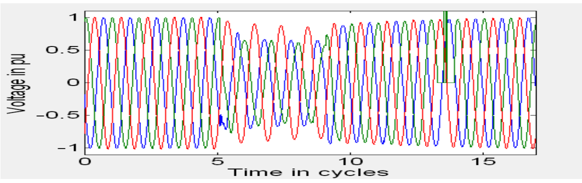

Figure 15. Measured sag with a clear post-fault component

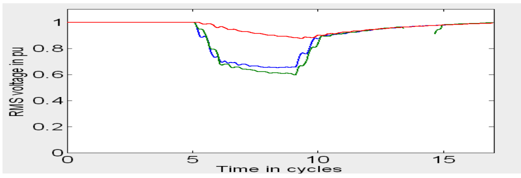

Figure 16. RMS voltages versus time for the sag shown in Figure 15

4. The Three Phases Unbalance

The three sequence component networks have to be connected into one equivalent circuit at the fault position. The connection of the sequence component networks depends on fault type. For a three-phase fault, all the three networks are shorted at the fault position. This leads to the standards voltage divider model for positive sequence and zero voltage, and current for the negative and zero sequences [8].

4.1 Single-Phase Fault

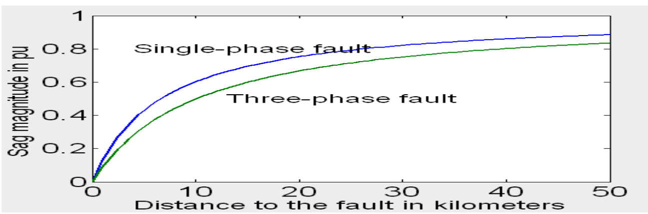

Figure 17. Voltage in the faulted phase for single-phase and three-phase faults on a 132 kV feeder

The difference is mainly due to the difference in feeder impedance. The zero-sequence feeder impedance increases faster than the positive-sequence impedance, with increasing distance to the fault. Therefore, single-phase fault leads to slightly smaller voltage drops than three phase faults.

4.2 Phase-to-phase Fault

In Figure 18, the circles and the arrows indicate the pre-fault voltages; the cross indicates the voltages in the faulted phases. The voltages in the two faulted phases move toward each other. The deviation of their path from a straight line is due to the difference in X/R ratio between source and feeder impedance.

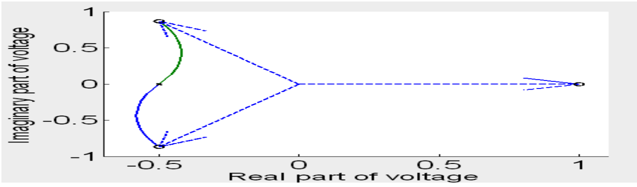

Figure 18. Complex voltages due to a phase-to-phase fault (solid line)

5. Phase-angle-jump

A short circuit in a power system not only causes a drop in voltage magnitude but also a change in the phase angle of the voltage. In a 50 Hz or 60 Hz system, voltage is a complex quantity (a phasor) which has magnitude and phase angle. A change in the system, like short circuit, causes change in voltage. This change is not limited to the magnitude of the phasor but includes a change in phase angle as well. The phase-angle jump manifests itself as a shift in zero crossing of the instantaneous voltage. The phase-angle jumps are not concern for most equipment. But power electronics converters using phase-angle information for their firing instants may be affected.

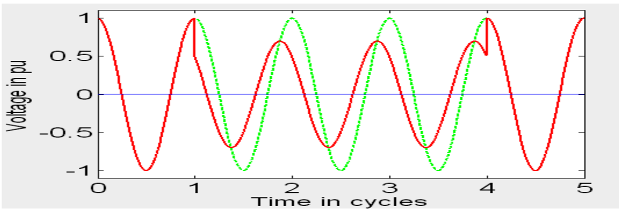

Figure 19. Synthetic sag with a magnitude of 70% and a phase-angle jump of +45^0

5.1 Monitoring

To obtain the phase-angle jump of measured sag, the phase-angle of the voltage during the sag must be compared with the phase-angle of the voltage before the sag. The phase-angle of the voltage can be obtained from the voltage zero-crossing or from the phase of the fundamental component of the voltage. The complex fundamental voltage can be obtained by doing a Fourier transform on the signal. This enables the use of Fast-Fourier Transform (FFT) algorithms.

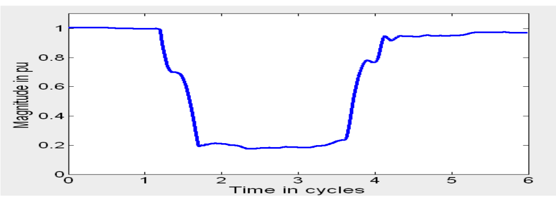

Figure 20. Amplitude of the fundamental voltage versus time for the voltage sag

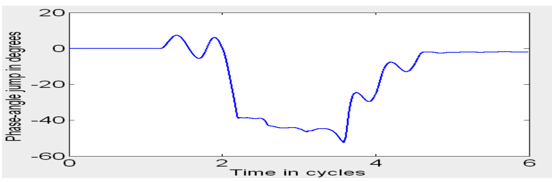

Figure 21. Argument of the fundamental voltage versus time for the voltage sag for half-cycle window

5.2 Influence of Source Strength

A strong source makes the sag less severe, less drop in magnitude as well as a smaller-phase angle jump. The only exception is for terminal faults. The phase-angle jump for zero distance to the fault is independent of the source strength. This is only of theoretical value as the phase angle-jump for zero distance to the fault, and thus for zero voltage magnitude, has no physical meaning [6].

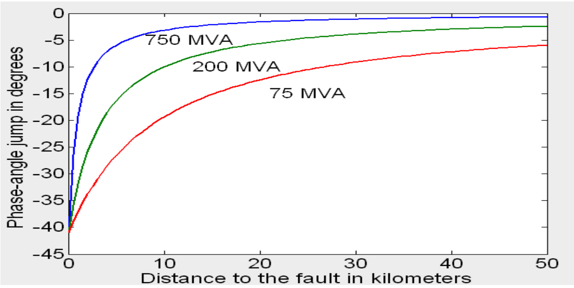

Figure 22. Phase-angle jump versus distance, for faults on a 150 mm^2 11 kV overhead feeder, with different source strength

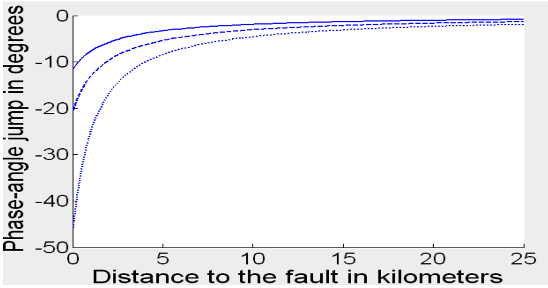

Figure 23. Phase-angle jump versus distance, for overhead lines with cross section 300 mm^2 (solid line), 150 mm^2 (dashed line), and 50 mm^2 (dotted line)

5.3 Influence of Cross Section

Figure 23 shows the phase-angle jump versus distance for 11kV overhead lines of different cross sections. The resistance of the source has been neglected i.e. Rs=0. The X/R ratio of the feeder impedances: 1.0 for the 50 mm^2 line, 2.7 for the 150 mm^2, 4.9 for the 300 mm^2; the phase-angle jump decreases for larger X/R ratio of the feeder.

6. Magnitude and Phase-angle Jumps for Three-phase Unbalanced Sags

The magnitude of a three-phase unbalanced sag is the RMS value of the lowest of the three voltages. The three magnitudes and phase-angle jumps are absolute value and argument, respectively, of a complex voltage [8].

- The initial complex voltage
- The characteristic complex voltage
- The complex voltages at the equipment terminals

Figure 24. shows the details of RMS values of the phase-to-ground voltages for the sag.

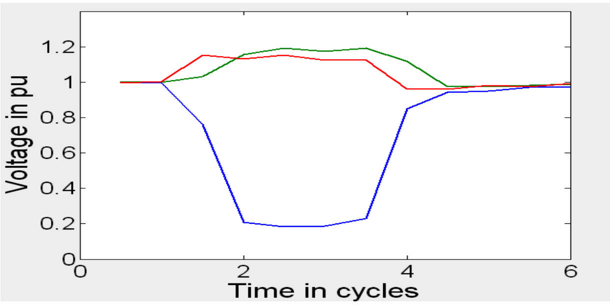

Figure 24. RMS values of the phase-to-ground voltages for the sag

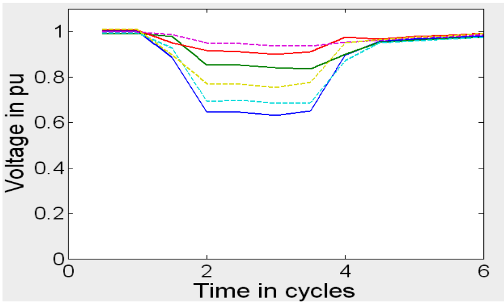

Figure 25. shows the details of The RMS values of the phase-to-phase (dashed lines) and phase-to-ground voltages after removal of the zero sequence component (solid lines) for the sag.

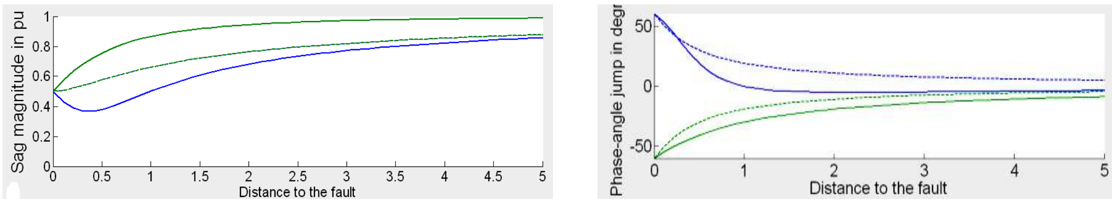

Figure 26. (a) and (b) show the details of Magnitude (top) and phase-angle jump (bottom) for sags of type C due to phase-to-phase faults. Dashed line: zero impedance angle (no characteristic phase-angle jump). Solid line:-60^0 impedance angle (large characteristic phase-angle jump).

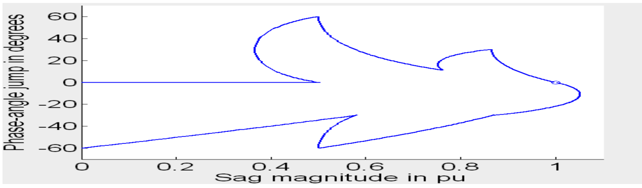

Figure 27 shows the details Range of sags due to phase-to-phase faults, as experienced by single-phase equipment.

7. Mitigation Methods Using Custom Power Devices
7.1 From Fault to Trip

We considered voltage magnitude events (voltage sags, short interruptions, and long interruptions) in detail: their origin, methods of characterization, monitoring and prediction, and their effects on equipment. Here, we look at the existing ways of mitigating voltage magnitude events. To understand the various ways of mitigation, the mechanism leads to an equipment trip need to be understood. Figure 28 shows how a short circuit leads to an equipment trip. The equipment trip is what makes the event a problem, if there were no equipment trips, there would not be any voltage quality problem. The underlying event of the equipment trip is a short- circuit fault: a low impedance connection between two or more phases, or between one or more phases and ground. At the fault position, the voltage drops to a low value. The effect of the short circuit at other positions in the system is an event of a certain magnitude and duration at the interface between the equipment and the power system. The short circuit fault has always caused voltage sag for some customers. If the fault takes place in a radial part of the system, the protection intervention clearing the fault has also lead to an interruption. If there is sufficient redundancy present, the short circuit has only lead to voltage sag. If the resulting event exceeds a certain severity, it has cause an equipment trip. Admittedly, not only short circuits lead to equipment trips, but also events like capacitor switching or voltage sags due to motor starting. But the large majority of equipment trips have been due to short circuit fault. Most of the reason to follow also applies to any other event, potentially leading to an equipment trip.

Figure 28 enables us to distinguish between the various mitigation methods:

1. Reducing the number of short circuit fault
2. Reducing the fault clearing time
3. Changing the system such short circuit fault results in less severe events at the equipment terminal or at the customer interface
4. Connecting mitigation equipment between the sensitive equipment and the supply
5. Improving the immunity of the equipment

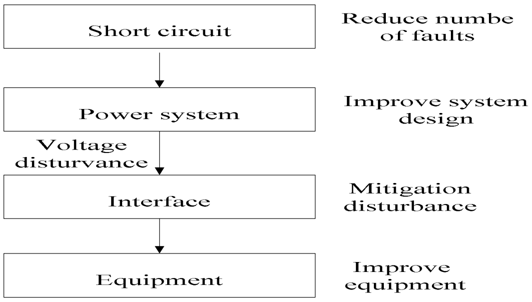

Figure 28. The voltage quality problem and ways of mitigation

Power system design and mitigation equipment at the system-equipment interface are considered in detail. Power engineers have always used a combination of these mitigation methods to ensure a reliable operation of equipment. Classically, the emphasis has been reduced the number of interruptions, while recently emphasis has shifted toward mitigation voltage sag.

7.2 Reducing the Fault-Clearing Time

Reducing the fault-clearing time does not reduce the number of events, but it is only their severity. It does not do anything to reduce the number or duration of interruptions. The duration of an interruption is determined by the speed which the supply is restored. Faster fault-clearing time does not also affect the number of voltage sags, but it can significantly limit the sag duration.

The ultimate reduction in fault-clearing time is achieved by using current-limiting fuses. Current-limiting fuses are able to clear a fault within one half-cycle, so that the duration of voltage sag has rarely exceeded one cycle. If we further realize that fuses have an extremely small chance of fail-to-trip, we migth have to look what the ultimate solution. The recently introduced static circuit breaker also gives a fault-clearing time within one half-cycle, but it is obviously more expensive than a current-limiting fuse. No information is available about the probability of fail-to-trip.

One important restriction of these devices is it can only be used for low and medium-voltage systems. The maximum operating voltage is a few tens of kilovolts. Static circuit breakers show the potential to be able to operate at higher voltage levels.

7.3 Changing the Power System

By implementing changes in the supply system, the severity of the event can be reduced. Here, the costs become very high, especially for transmission and sub transmission voltage levels. The main mitigation method against interruptions is the installation of redundant components. Mitigation method especially directed toward voltage sags are:

Install a generator near the sensitive load. The generators have kept the voltage up during sag due to remote fault. The reduction in voltage drop is equal to the percentage contribution of the generator station to the fault current. In case a combined heat and power station is planned, it is worth to consider the position of its electrical connection to the supply.

1. Split busses or sub stations in the supply path to limit the number of feeders in the exposed area.
2. Install current limiting coils at strategic places in the system to increase the electrical distance to the fault. One should realize that this can make sag worse for other customers.
3. Feed the bus with sensitive equipment from two or more sub stations. A voltage sag in one sub station will be mitigated by the infeed from the other sub stations. The more independent sub stations, the more mitigation effect. The best mitigation effect is by feeding from two different transmission sub stations. Introducing the second infeed increases the number of sags, but reduces their severity.

7.4 Installing Mitigation Equipment

The most common applied method of mitigation is the installation of additional equipment as the system equipment interface. Recent developments point toward a continued interest in this way of mitigation. The popularity of mitigation equipment is being the only place where the customer has control over the situation. Both changes in the supply as well as the improvement of the equipment are often completely outside the control of the end user.

Some mitigation equipments are:

1. Uninterruptable power supplies (UPSs) are extremely popular for computers: personal computers, central servers and process control equipments.
2. Motor generator sets are often depicted as noisy and need maintenance. But in industrial environments, noisy and maintenance on rotating machines are normal. Large battery blocks also require maintenance, which the expertise is less available.
3. Voltage source converters (VSCs) generate a sinusoidal voltage with the required magnitude and phase, by switching a dc voltage in particular way over the three phases. This voltage source can be used to mitigate voltage sags and interruptions.

7.5 Improving Equipment Immunity

Improvement of equipment immunity is probably the most effective solution against equipment trips due to voltage sags. But it is often not suitable as a short-time solution. A customer often only finds out about equipment immunity after the equipment has been installed. For consumer electronics, it is very hard for a customer to find out the immunity of equipment. Even most adjustable-speed drives have become off-the-shelf equipment where the customer has no influence on the specifications. Only large industrial equipment is custom-made for a certain application, which enables the incorporation of voltage-tolerance equipment.

Some specific solutions toward improved equipment are:

1. The immunity of customer electronics, computers, and control equipment can be significantly improved by connecting more capacitance to the internal dc bus. This has increased the maximum sag duration which can be tolerated.
2. Single phase low-power equipment can also be improved by using a more sophisticated dc/dc converter: one which is able to operate over a wider range of input voltages. This has reduced the minimum voltage for which the equipment is able to operate properly.
3. The main source of concern is adjustable-speed drives. The ac drives can be made to tolerate sags due to single phase and phase-to-phase fault by adding capacitance to the dc bus. To achieve tolerance against sags due to three-phase fault, serious improvements in the inverter on rectifier are needed.
4. Improving the immunity of dc adjustable-speed drive is very difficult because the armature current, and thus the torque, drops very fast. The mitigation method has been much depends on restriction imposed by the application of the drive.
5. Apart from improving (power) electronic equipment like drives and process control computers, a thorough inspection of the immunity of all contactors, relays sensors, etc. can also significantly improved the process ride through.

8. Power System Design-Redundancy through Parallel Operation

8.1 Parallel and Loop System:

Figure 29 shows a public distribution network with a higher nominal voltage. It serves more customers, so it is worth to invest more in reliability. Part of the system is still operated in a radial way with normally open points. The majority of the 33 kV system is operated with parallel feeders. Both paths carry part of the load. If one path fails, the other path takes over the supply instantaneously. Also the 33/11 kV transformer and the 33 kV substation bus are operated in parallel. The rating of each component is such that the load can be fully supplied if one component fails.

Figure 29 also shows the two type of parallel operation: two feeders are in parallel and a loop system. In both cases, there is single redundancy. The loop system is significantly is cheaper, especially in case of transformer connections. But the voltage control of loop systems is more difficult.

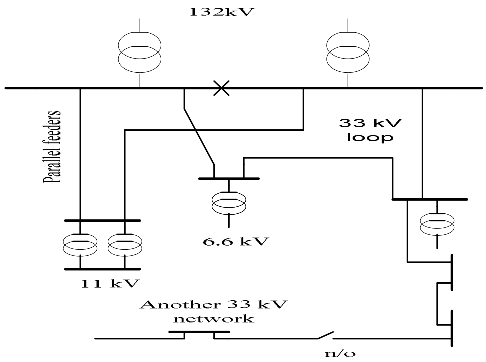

Figure 29. Distribution network with redundancy through parallel operation

8.2 Design Criteria for Parallel and Loop System

The design of the parallel and loop system is based on the so called (n-1) criterion, which states that the system consisting of n components should be able to operate with only (n-1) components in operation, thus with one component out of the operation. This should hold for any one component out of operation. The (n-1) criterion is very commonly used in power system design. It enables a high reliability without the need for stochastic assessment. In some cases (large transmission systems, generator scheduling), (n-2) or (n-3) criteria are used.

Here, we concentrate on (n-1) criterion, also referred as “single redundancy”. This criterion is very commonly used in design of the industrial medium-voltage distribution as well as in public submission systems. The main design rule is that no single event should lead to an interruption of the supply to any of customers. In any industrial environment, the wording is somewhat different; no single event should lead to a production stop for any of the plants. How these basic rules are further developed depends on the kind of the system. A list of things that have to be considered is given below.

1. The obvious first rule is no component outages lead to an interruption. There should be an alternate path for the power flow through any component.
2. There should be not only an alternate path for the power flow, but this alternate path should also not lead to an overload situation. In the public supply, the load demand varies significantly during the day. A certain amount of overload can be tolerated for a few hours. In industrial system, the load is typically more constant, so that any overload would be permanent. However, in industrial system, it is often easier to reduce the load on a time scale of hours or to start on-site generation.
3. The power system protection should be able to clear any fault without causing an interruption for any of customers. This requires more complicated protection systems than for radial-operated network. These protection systems require additional voltage transformer and/or communication links. Also the numbers of circuit breakers increase, two circuit breakers are needed for each connection between two substations in a loop or parallel system.
4. Voltage fluctuations due to rapid load fluctuations and voltage sags due to motor starting should be within limits for any one component out of operation. This translates into a minimum fault level for any load bus. The switchgear rating dictates a maximum fault level for the system with all components in operation. The optimal use of this margin between maximum and minimum fault level is one of the main challenges in the design of industrial medium-voltage distribution systems.
5. The electromechanical transient due to a short circuit in the system with all components in operation should not lead to loss of any load. In industrial systems with a large fraction of induction motor load, it must be ensured that these motors are able to re-accelerate after the fault.
6. The voltage sag due to any fault in the system should not lead to tripping of essential load with any of customers.

8.3 Voltage Sags in Parallel and loop systems

The magnitude of voltage sags due to fault is shown in Figure 30. This has been used to assess the number of voltage sags experienced by the plant.

For the radial system, the plant has been experienced interruption due to fault on 25 km of overhead line, and voltage sags due to fault on 200 km of line. The relation between sag magnitude and distance to the fault is according to dotted line shown.

For radically operated systems, without a connection to bus II, the voltage at the load bus is equal to the voltage at bus I. Figure 31 compares the voltage magnitude at the load bus for two design alternatives. It is obvious that the second infeed significantly reduces the voltage drop.

The deepest sag has a magnitude of 50% of nominal. Here, it is assumed that the second transformer has the same impedance as the first one. In practice, this translates to them having the same rating. If the second transformer has the smaller rating, its impedance has typically been higher and voltage sag has been deeper.

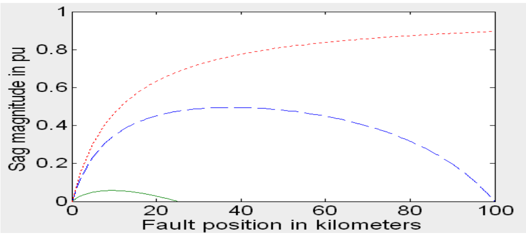

Figure 30. Sag magnitude as a function of fault position for fault in the system: Solid line: fault on the 25 km branch of a 125 km loop; dashed line: fault on the 100 km branch of a 125 km loop; dotted line: faults on a radial feeder.

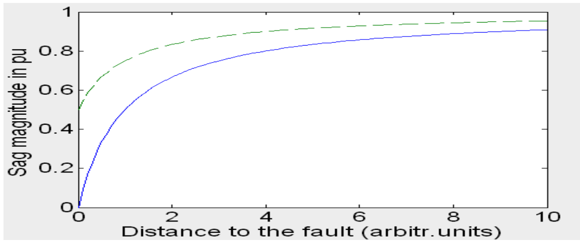

Figure 31. Sag magnitude as a distance to the fault, without (solid line) and with (dashed- line) a connection to a second substation at a higher voltage level

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From the expression for the voltage versus distance, we can obtain expressions for the critical distance. For radial system we obtain the expression:

$$l_{crit} = \frac{V}{1-V} \tag{4}$$

For the system with double infeed, we obtain:

$$l_{crit} = \frac{V - \frac{1}{2}}{1-V}, \quad V \geq 0.5 \tag{5}$$

And $l_{crit} = 0$ for $V < 0.5$ from the critical distance the exposed length can be calculated, as shown in Figure 32. The main feature is the exposed length is zero in case the equipment can tolerate sag down to 50% of nominal. This could be important piece of information in deciding the voltage tolerance requirement for the load. For higher critical voltages (more sensitive equipment), the exposed length depends on the number of feeders originating from the two busses.

If the distance between the substations has been increased to 100 km, all other parameter was kept the same. Figure 33 shows the sag magnitude as a function of the fault position. The voltage in sub transmission system is approximated by the average voltage in the two transmission substations. This voltage is indicated by the dotted line in Figure 33.

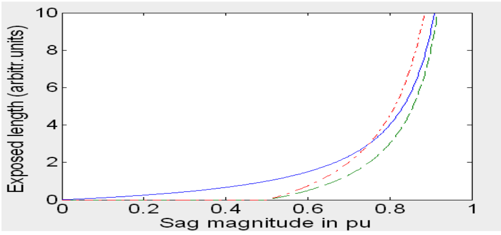

Figure 32. Exposed length for radial supply (solid line) and for a connection to a second substation at a higher voltage level: same number of feeders from both substations (dashed line); twice as many feeders from the second substation (dash-dot line)

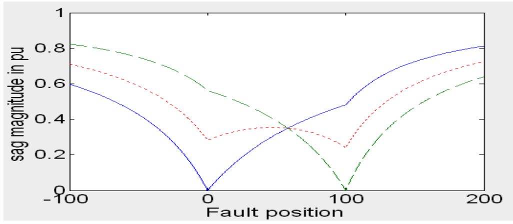

Figure 33. Sag magnitude in transmission and sub transmission systems
Solid line: transmission substation 1, dashed line: transmission substation 2, dotted line: sub-transmission

9. Series Voltage Controllers-DVR

9.1 Basic Principle

The series voltage controller consists of a voltage source converter in series with the supply voltage as shown in Figure 34. The voltage at the load terminal equals the sum of the supply voltage and output voltage of the controller.

$$\bar{V}_{load} = \bar{V}_{cont} + \bar{V}_{sag} \tag{6}$$

A converter transformer is used to connect the output of the voltage-source converter to the system. A relative small capacitor is present on dc side of the converter. The voltage over this capacitor is kept constant, by exchanging energy with energy storage reservoir. The required output voltage is obtained by using a pulse-width modulation switching pattern. As the controllers have to supply active as well as reactive, some kind of energy storage is needed.

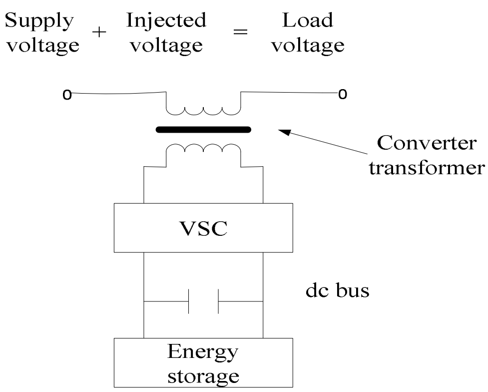

Figure 34. Series voltage controller

The term Dynamic Voltage Restorer (DVR) is commonly used instead of series voltage controllers. In the DVR that are currently commercially available large capacitors are used as a source of energy. Other potential sources are being considered: battery banks, superconducting coils, flywheels.

The amount of energy storage depends on the power delivered by the converter and on the maximum sag duration and certain minimum sag voltage.

The active power requirement is linearly proportional to the drop in voltage. When phase-angle jumps are considered, the relation is no longer linear and becomes depend on the power factor also. To assess the effect of phase-angle jump and power factor, we have used relation between sag magnitude and phase-angle jump. The active power requirement for different power factor and different phase-angle jump is shown in Figure 35. Sag magnitude and phase-angle jump have been calculated as a function of the distance to the fault. Magnitude and phase-angle jump were calculated for different values of the impedance angle. These are plotted as a function of the sag magnitude V.

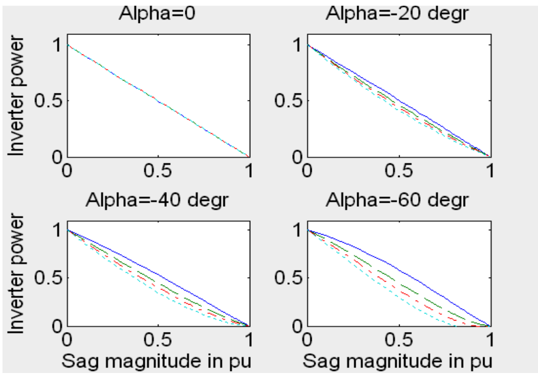

Figure 35. Active power requirement for a series voltage controller, for different impedance angles (α=0, -20^0, -40^0, -60^0) and different lagging power factors: 1.0 (solid lines), 0.9 (dashed lines), 0.8 (dash-dot lines), 0.7 (dotted lines).

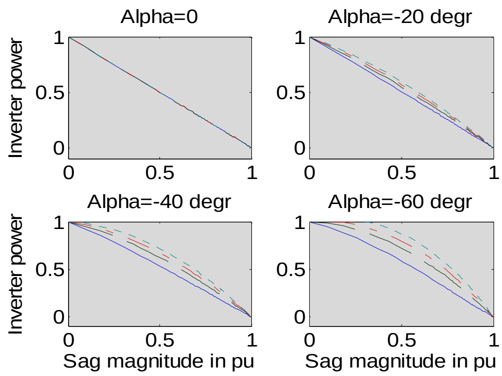

Figure 36. Active power requirement for a series voltage controller, for different impedance angles (α=0,-20^0,-40^0,-60^0) and different leading power factors: 1.0 (solid lines), 0.9 (dashed lines), 0.8 (dash-dot lines), 0.7(dotted lines)

Due to the phase-angle jump, the voltage at the system side of the controllers becomes more in phase with the load current. The amount of active power taken from the supply increase and the active power requirement of the controller is reduced. This holds for a negative phase-angle jump and a lagging power factor. For leading power factor, a negative phase-angle jump increases the active power requirement as shown in Figure 36.

9.2 Single-Phase Series Voltage Controllers

For single-phase controllers, the actual voltage in one phase determines the amount of active power which needs to be injected. This is not only determined by the characteristic magnitude, but also by the type of sag and the phase to which the controller is connected.

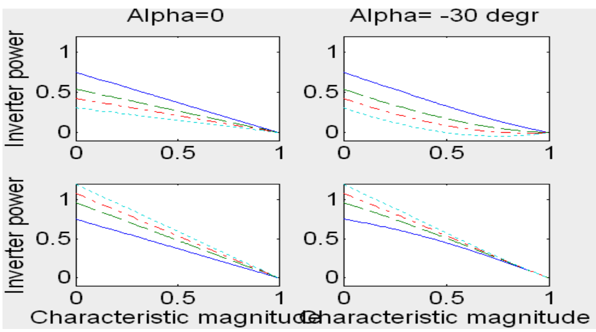

Figure 37. Active power requirement for a single-phase series voltage controller, for two phases of type C unbalanced sag, for impedance angle zero(left) and -30^0 (right). Power factor 1.0(solid lines), 0.9(dashed), 0.8(dash-dot), 0.7 (dotted).

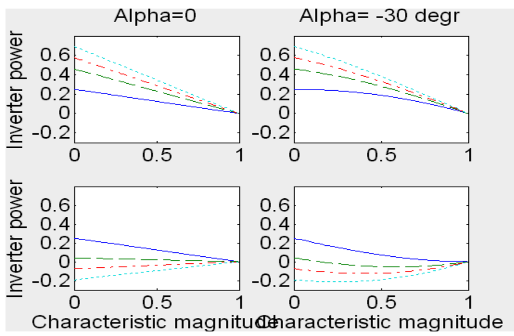

Figure 38. Active power requirement for a single-phase series voltage controller, for two phases of type D unbalanced sag, for impedance angle zero(left) and -30^0 (right). Power factor 1.0(solid lines), 0.9(dashed), 0.8(dash-dot), 0.7 (dotted)

What matters to a single-phase controller the injected powers in each of the three-phases are. These calculations have been performed for three-phase unbalanced sags of type C and type D, resulting in figure 37 and figure 38 respectively.

For each sag type only two phases have been plotted, the two phases with the deep sag for type C, and the two phases with the shallow sag for type D. Third phase for type C sag does not require any injected power, the active power requirement for the third phase of a type D sag are identical. Both in Figure 37 and Figure 38, the injected power has been plotted for two values of the impedance angle (0^0 and 30^0) and four values of the power factor of the current load (1.0, 0.9, 0.8, 0.7). We can conclude from the figures that power factor has significant influence on the power injection. The characteristic phase-angle jump makes the two phases behave slightly different, but does not change the overall picture.

For a single-phase controller, the characteristic voltage does not have much practical meaning. Therefore, the active power requirement has been plotted in a different way in Figure 39 and Figure 40. The horizontal axis is the absolute value of the complex voltage during the sag; in other words, the sag magnitude at the equipment terminal. The different curves in each sub plot give the relation between sag magnitude and injected power for each of the phases of type C or type D three-phase unbalanced sags. This leads to a maximum of five curves, two from type C sag, and three from type D sag. We see that there is no general relation between the injected power and the sag magnitude, especially for small values of the power factor. For low power factor, a zero-magnitude sag is not the one with the highest active power requirements.

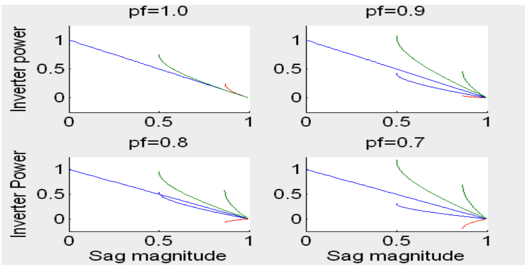

Figure 39. Active power requirements for a single-phase series voltage controller as a function of the sag magnitude-for zero impedance angle and four values of the power factor of the load current

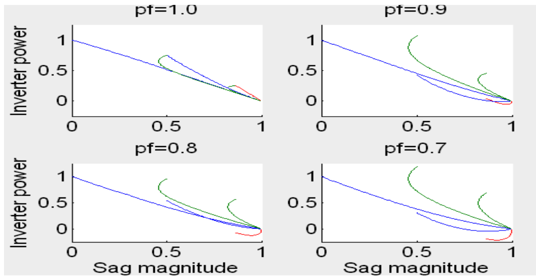

Figure 40. Active power requirements for a single-phase series voltage controller as a function of the sag magnitude-for an impedance angle equal to -30^0 and four values of the power factor of the load current

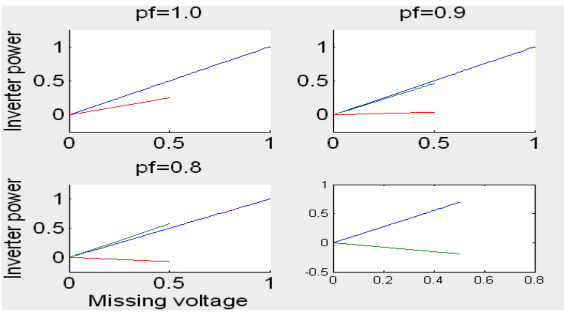

Figure 41. Active power requirements for a single-phase series voltage controller as a function of the missing voltage-for zero impedance angle and different values of power factor of load

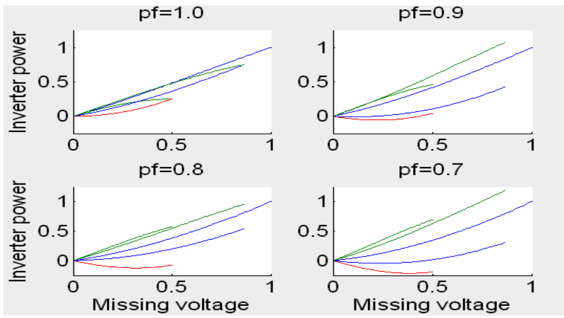

Figure 42. Active power requirements for a single-phase series voltage controller as a function of the missing voltage-for zero impedance angles equal to -30^0 and four values of the power factor of the load current

Figure 39 and Figure 40 have been reproduced in Figure 41 and Figure 42 with yet another horizontal axis. The active power requirements have been plotted as a function of the absolute value of the complex missing voltage. We also see that the missing voltage does not uniquely determine the injected power. The load power factor and, to a lesser extent, the characteristic phase-angle jump influence the injected power as well and should be considered in dimensioning the energy storage of the controller.

10. Shunt Voltage Controllers-STATCOM

A shunt-connected voltage controller is normally not used for voltage sag mitigation, but for limiting reactive power fluctuations or harmonic currents taken by the load. Such a controller is commonly referred to as a "Static Compensator" or "STATCOM". Alternative terms in use are "Advanced Static Var Compensator" (ASVC) and "Static Condenser" (STATCON). A STATCON does not contain any active power storage and thus only injects or draws reactive power as shown in Figure 43. Limited voltage sags mitigation is possible with the injection of reactive power only, but active power is needed if both magnitude and phase angle of the pre-event voltage need to be kept constant.

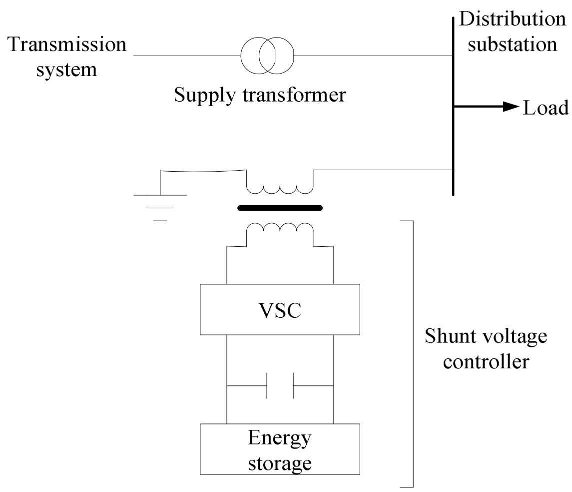

Figure 43. Shunt voltage controller

The main limitation of the shunt controller is the source impedance becomes very small for fault at the same voltage level close to the load. Mitigating, such sags through a shunt controller, is impractical as it would require very large currents. We, therefore, only consider fault upstream of the supply transformer. The minimum value of the source impedance is the transformer impedance. This configuration as a dedicated supply to a sensitive load (e.g. automobile plant), where the task of the controller is to mitigate sags originating upstream of the transformer. The result is shown in Figure 44. Four different values of the source impedance (transformer impedance) have been used: 0.1, 0.05, 0.033, and 0.025 p.u. For the load impedance, a value of 1 p.u. resistive has been chosen. For a 0.05 p.u. source impedance, the fault level is 20 times the load power. Fault levels of 10 to 40 times the load are typical in distribution systems. For increasing impedance angle, we see an increase in active power, especially for smaller values of the source impedance. The reactive power, as shown in Figure 44, is rather independent of the impedance angle. The reactive power requirements decrease significantly with the increasing source impedance. As the reactive source impedance increases, less injected current is needed to get the same change in voltage. The reactive power exceeds the active power injected in all shown situations.

The current rating of the controller is determined by both active and reactive power. The absolute value of the injected current as follows:

$$I_{cont} = \sqrt{\frac{1 - 2V\cos\psi + V^2}{R^2 + X^2}} \quad (7)$$

We saw that an increasing phase-angle jump (increasing ψ, decreasing $\cos\psi$) increases the current magnitude. The current magnitude is plotted in Figure 44. as in the same format as the reactive power in Figure 45.

Comparing Figure 45 with Figure 44 shows that the current magnitude is mainly determined by the reactive power. Like the reactive power, the current magnitude is only marginally affected by the phase-angle jump.

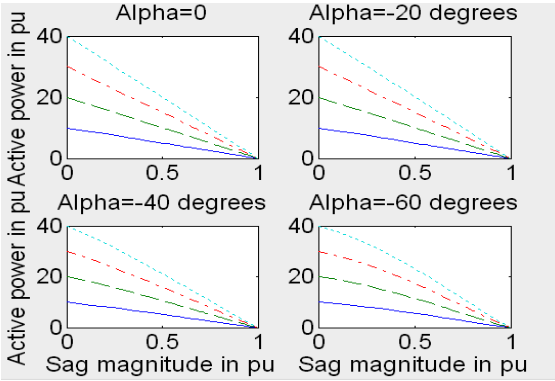

Figure 44. Reactive power injected by a shunt voltage controller, for different impedance angles (0, -20^0, -40^0, -60^0) and different source impedances: 0.1pu (solid line), 0.05pu (dashed line), 0.033pu (dash-dot line), 0.025pu (dotted line)

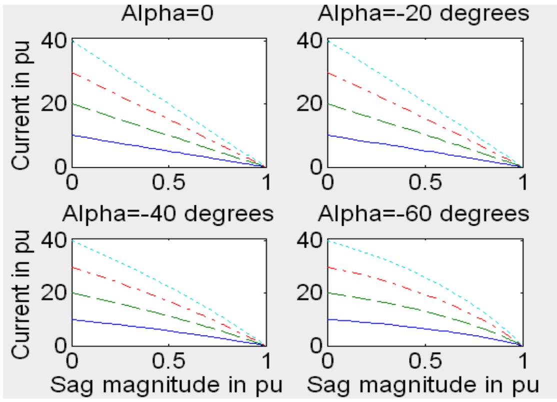

Figure 45. Magnitude of the current injected by a shunt voltage controller, for different impedance angles (0, -20^0, -40^0, -60^0) and different source impedances: 0.1pu (solid line), 0.05pu (dashed line), 0.033pu (dash-dot line), 0.025pu (dotted line)

11. Combined Shunt and Series Controllers

The series controllers use an energy storage reservoir to power part of the load during a voltage sag. The series controller cannot mitigate any interruptions, and that is normally not designed to mitigate very deep sags (much below 50% of the remaining voltage).

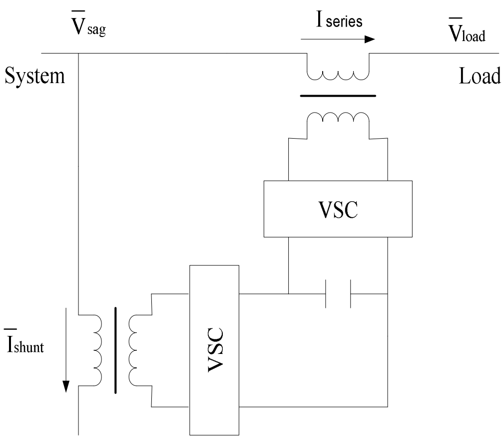

Figure 46. Shunt-series-connected voltage controller: the shunt-connected converter is placed on system side of the series controller

There is normally some voltage remaining in the power system. This voltage can be used to extract the required energy from the system. A series connected converter injects the missing voltage, and a shunt controller converter takes a current from the supply. The principle is shown in Figure 46. Series and shunt connected converter have a common dc bus. The change in stored energy in the capacitor is determined by the difference between the power injected by the series converter and the power taken from the supply by the shunt converter. Ensuring that both are equal minimizes the size of the capacitance.

12. Conclusions

The voltage sag and their characterization have been presented for different conditions. The voltage sag depends on voltage rating and cross sectional area. The sag magnitude increases (i.e. the sag becomes less severe) for increasing distance to the fault and for increasing fault level. The fault at tens of kilometers distance may cause severe sag. A stronger source makes the sag less severe, less drop in magnitude as well as a smaller-phase angle jump. The phase-angle jump for zero distance to the fault is independent of the source strength. Overhead lines and cables of different cross section have different impedance. Hence, the cross section of the line or cable influences the sag magnitude. The missing voltage distribution curve can be used as a generalized way of defining the event duration. The larger the deviation from the ideal voltage one considers, the shorter would be the “cumulative duration” of the event. The cumulative duration of voltage sag for a given deviation is defined as the total amount of time during which the voltage deviates more than the given value from the ideal voltage wave shape. Different protection options for improving performance, during power quality variation, by using Dynamic Voltage Restorer (DVR), Distribution Static Compensator (DSTATCOM), and Solid State Transfer Switch (SSTS) etc. studied for mitigation of sags and interruptions.

The shunt and series controllers are based on power-electronic voltage source converters. Through these converters, it is possible to compensate for the drop in system voltage or even temporarily to take over the supply completely. For not too deep voltage sags, it is possible to compensate the drop in voltage magnitude by injecting reactive power only, but for a full compensation both reactive and active power are needed.

On compares the voltage magnitudes at the load bus for two design alternatives, it is immediately obvious that the second in feed significantly reduces the voltage drop. The deepest sag will have a magnitude of 50% of nominal. From the critical distance, the exposed length can be calculated. For higher critical voltages (more sensitive equipment), the exposed length depends on the number of feeders originating from the two busses. The distance between the substations has been increased to 100 km, all other parameter were kept. The amount of active power taken from the supply thus increases and the active power requirement of the controller is reduced. For leading power factor, a negative phase-angle jump increases the active power requirement. A single-phase controller is the injected powers in each of the three-phases. For a single-phase controller, the characteristic voltage does not have much practical meanings. For increasing impedance angle, we observed an increase in active power, especially for smaller values of the source impedance.

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